Weak Lensing Induced Correlations between 1Jy QSOs and APM galaxies on Angular Scales of a Degree

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ABSTRACT

We find angular correlations between high redshift radio selected QSOs from the 1 Jy Catalog and APM galaxies on $\lesssim 1^\circ$ scales. We demonstrate that observed correlations are qualitatively consistant with a gravitational lensing explanation and are inconsistant with a Galactic dust obscuration model. Comparing our results with those of Benítez & Martínez-González, who also use 1 Jy sources and APM galaxies we come to the conclusion that galaxy selection criteria can have a major effect on the angular scale and amplitude of detected correlations.

1. INTRODUCTION

Large-scale matter inhomogeneities at low redshifts ($z \lesssim 0.5$) can have a profound effect on how we perceive the high redshift universe. Weak gravitational lensing is expected to produce statistical association of background QSOs and foreground galaxies due to a phenomenon known as magnification bias (Turner 1980, Canizares 1981). Magnification bias arises because gravitational lensing changes the solid angle of a source but conserves its surface brightness. Faint background objects are brightened into a flux limited sample while their number density on the sky is diluted. These two effects lead to opposite results in the observed number density of the sources. If the slope of the magnitude-number counts is steep enough such that the enhancement of the number density due to source brightening 'wins' over the geometrical dilution then an overdensity is observed. The opposite is true if the source number counts are shallow. Any single object is not expected to confirm the presence of magnification bias because the large-scale lensing effect is weak, the intrinsic luminosities of individual sources are not known, and the number density variation of galaxies due to large-scale structure is large. However, a large enough sample of sources with steep number counts will show an effect of magnification bias in a statistical sense: an overdensity of sources behind lenses will be observed.

Several studies have detected statistical associations of bright background QSOs with foreground galaxies, believed to be tracers of the lensing mass (e.g. Tyson 1986, Bartelmann & Schneider 1997, Norman & Impey 1999, and references within). The scale over which an enhancement of galaxies is seen is important to the determination of the size of the foreground lens structures, as the angular scale of association can be translated to the physical scale when the redshifts of the lenses (galaxies, clusters) are known. Most studies

have focused on scales $< 15'$, or $< 2h^{-1}$Mpc at the redshifts of typical lenses. In these cases, when the slope of the number counts of the source sample has been steep enough ($d\log N/dm = \alpha > 0.4$), positive correlations have been detected (Fugmann 1990, Benítez & Martínez-González 1995, 1997). In the case where the slope has been < 0.4, anti-correlations are seen (Croom & Shanks 1999, hereafter CS99), as predicted by magnification bias due to lensing.

Four studies have looked at overdensities on scales $> 30'$, i.e. $> 5h^{-1}$Mpc. Rodrigues-Williams and Hogan (1994) detect correlations of Zwicky clusters and LBQS QSOs (Hewett et al. 1995) with redshifts $z = 1.4 - 2.2$ on degree angular scales. Seitz and Schneider (1995) extended this study to include 1 Jy QSOs. These QSOs show an association with Zwicky clusters with a significance of 97.7% on similar scales. Ferreras et al. (1997) observed a strong anti-correlation between faint optically selected QSOs at $z < 1.6$ near the North Galactic Pole. However, the authors attribute this effect to selection biases associated with identifying QSOs in crowded regions. Finally, Williams & Irwin (1998, hereafter, WI98), detected overdensities of APM galaxies around optically selected LBQS QSOs on scales of about a degree. In particular they find that the galaxies primarily responsible for the detected overdensity are red with an average B−R = 2.1.

Though qualitative characteristics of these positive associations between QSOs and galaxies are consistent with weak lensing, two explanations for the observations have been proposed; (1) a brightening of QSOs due to gravitational lensing by foreground matter overdensities, as described above, and (2) patchy obscuration of QSOs and galaxies by intervening Galactic dust. However, with a proper choice of background sources it is possible to distinguish between these two theories. For example, if dust obscuration is the reason for the observed galaxy overdensity around QSOs, then a source population that is less sensitive to dust obscuration, e.g., a radio selected QSO sample, should show less of an effect than one that is more sensitive to dust, like a optically selected sample. If lensing is the correct explanation, then such a radio sample will show a stronger association.

This test provides motivation for the present paper where we extend the work of WI98, who used optically selected QSOs, to a sample of radio selected QSOs. We have taken QSOs from the 1 Jy radio source catalog (Kühr et al. 1981) and searched for overdensities of APM galaxies in radial regions of $30'$ and $60'$ around these QSOs. In section 2, we discuss these catalogs along with the data selection criteria. In section 3 we show that the correlations between 1 Jy QSOs and APM galaxies exist and are statistically significant. In sections 4, 5, and 6 we present evidence that the correlations are due to the magnification bias of weak lensing, and study the depence of correlations on the angular scale and the type of galaxies used in the analysis. Section 7 summarizes our findings and compares them to existing lensing models.

2. DATA

Our QSO sample is chosen from the 1 Jy all-sky catalog (Kühr et al. 1981). The catalog lists 527 radio sources with flux densities of $f_{5GHz} \geq 1.0$ Jy and covers 9.81 sr of sky at Galactic latitudes $\mid b \mid \geq \pm 10°$. 97% of the radio sources have also been optically identified (Stickel et al. 1994). We limit our sample to those QSOs with redshifts ≥ 0.5 since we would like to study the association of foreground to background objects and not galaxies in the local environment of the QSOs. For this study we have also chosen only those QSOs with positions on the Palomar plates (northern hemisphere) of the APM survey. The histogram in Figure 1 shows the redshift distribution of our radio QSO sample.

The APM Catalogue (Irwin et al. 1994) is assembled from scans of the Palomar sky survey plates

taken in the northern hemisphere and the UKST sky survey southern hemisphere plates. Each plate covers $\sim 6^\circ$. The catalog lists objects detected on plates taken with red and blue filters separately, along with information about each object's morphology and magnitude in both filters. Morphology information includes a classification of the object as either star-like, extended, noise, or blended. The catalog is well calibrated internally, however, absolute magnitude calibrations of the data are only approximate. For this study the magnitude differences are not large, and our analysis (described below) compensates for these variations.

The Palomar plates were taken with O and E filters. The limiting magnitude for the survey is O = 21.5 (blue) and E = 20.0 (red).

We use the APM class and magnitude information to select our galaxy sample. We require that the galaxies in our sample have red magnitudes between 18.5 and 20.0, and are classified as extended in the red. We make no requirement on the blue classification or magnitude of the objects, except that the object must be detected on the blue plates. We also require that our QSOs be located within 2.5° of the plate center so as to reduce the effects of vignetting on the plates.

In order to check our results, we also select a sample of Galactic stars with the same red and blue criteria, but that are classified as star-like on the red plates.

The average O−E color of galaxies in our sample is $\sim$1.8. We use the color transformation of Totten & Irwin (1998) and determine our sample to have an average color B−R=1.4 This is approximately the color found for APM galaxies detected on the southern (UKST) plates for galaxies with $18.5 < m_{red} < 20.0$ (WI98, Maddox et al. 1996). Also, the red filter of the APM northern hemisphere plates is almost the same as the R filter of the UKST plates. We therefore estimate our galaxy sample to have a redshift distribution similar to the one in WI98, with a peak at z = 0.2 and nearly no galaxies extending beyond z = 0.7.

3. ANALYSIS

As we show below, radio selected QSOs from the 1 Jy Catalog correlate with foreground APM galaxies. The result in not entirely surprising as correlations have already been found between these two catalogs (Benítez & Martínez-González 1995, hereafter, BM95; Benítez & Martínez-González 1997). The important difference compared to the earlier studies is that we use different galaxy selection criteria which allows us to probe the correlations on much larger angular scales.

Our goals in this paper are twofold. First we would like to determine if Galactic dust obscuration is responsible for the observed cross correlations. Second, we would like to determine what angular scales the signal is coming from. If the correct interpretation of the signal is weak lensing, the angular scale translates into the physical size of the large scale structure responsible for the correlations. We also explore a related issue: how does the scale of correlations depend on the type of galaxies being used in the analysis.

As mentioned in the Introduction, the two main physical reasons for the cross correlation signal, namely weak lensing and dust, can be diffentiated by comparing radio and optically selected samples of QSOs. Moreover, dust and lensing will produce qualitatively different trends when QSO-galaxy cross-correlations are studied as a function of QSO redshift and apparent magnitude, or limiting radio flux. For example, dust-induced correlations are expected to be of similar amplitude for QSOs of all redshifts, whereas lensing should preferentially affect QSOs in the 'optimal' redshift range.

Therefore we would like to study how the correlations are affected by QSO properties. A compact way of summarizing the behaviour of cross-correlations on a single angular scale is as follows. QSOs are divided into subsamples with limiting apparent optical magnitude, $m_{Q,lim}$ or radio flux, $f_{Q,min}$, and a lower redshift cutoff, $z_{Q,min}$. Galaxies inside a circle of radius θ around each QSO are counted. For each QSO 100 random positions are chosen on the same APM plate, and at the same distance from the plate center as the QSO itself to minimize the effects of vignatting. The galaxy counts in these 100 circular regions are used as comparison counts. Overdensity is then the ratio of the galaxy density around the real QSO and the average density in 100 randomly chosen circles.

To determine the statistical significance of the correlations in a model independent way we create 100 simulated observations, and compute the fraction of cases in which the over- or underdensity of galaxies is more extreme than in the real case. For each simulated observation the galaxy density around a 'simulated' QSO is picked from 100 randomly chosen positions.

To make sure that the signal is not an artifact of plate sensitivity gradients or plate defects we repeat the entire procedure with Galactic stars instead of galaxies.

The results, for $30'$ and $60'$ circles are presented in Figures 2-5, as contour plots. The top (bottom) panels are the QSO-galaxy (QSO-star) correlations, estimated as the overdensity of galaxies (stars) around QSOs. The left (right) panels show overdensity (statistical significance). Overdensity contours are at 5, 10, 20% levels for $30'$ cases, and at 5, 10% for $60'$ cases, with underdensities shown as dashed lines. Thickest lines represent the largest over- and underdensities. Statistical significance is plotted at 90 and 98% confidence levels. The shaded region in each panel marks subsamples with less than 5 QSOs. Figures 2 and 4 use QSOs of all radio fluxes, i.e. $f_{Q,min} = 1$Jy, and show how the signal changes with apparent optical magnitude cutoff, while Figures 3 and 5 have QSOs of all optical magnitudes, down to $m_V \sim 21 - 22$, and show how correlations behave as $f_{Q,min}$ is changed.

All figures show a statistically significant cross correlation signal between QSOs and foreground galaxies, while the control correlations with Galactic stars do not show any significant signal. Next we discuss two possible physical interpretations of the detected signal.

4. PHYSICAL INTERPRETATION: DUST VS. LENSING

All QSOs and galaxies are seen through the Galactic dust which is known to be patchy and extend to high Galactic latitudes (Burstein & Heiles 1982, Schlegel et al. 1998). Directions on the sky suffering more dust obscuration will show decreased counts of galaxies and QSOs thus leading to an apparent cross correlation between these two classes of objects. Even though radio selected sources will be less affected by dust than optically selected ones, they are still not completely free from dust effects because every radio selected QSO must be further detected and its redshift determined by optical means. If dust is the primary reason for the observed correlations then a radio selected sample should show weaker correlations than a comparably-sized optically selected sample.

The WI98 and the present study are well suited for such a comparison test, as the same catalog of foreground galaxies, namely APM, is used in both cases. The observed situation is the opposite of the dust hypothesis prediction: radio selected sample with no optical flux cut shows stronger correlations than the optically selected sample with no radio flux cut, on $30' - 60'$ scales, as can be seen from all the data presented in Figures 2-5. These results are fully consistent with the double magnification bias due to

lensing, which predicts that the cross correlation signal will become stronger if QSOs are flux-limited in more than one independent wavelength bands simultaneously (Borgeest et al. 1991), optical and radio, in this case.

A further test was performed to detect lensing double magnification bias. We repeated the calculations for Figure 2 ($m_{Q,lim}$ QSO subsamples with no radio flux cut, $\theta = 30'$) with an additional condition that $f_{Q,min} = 1.25$Jy for all QSOs; see Figure 6. The correlations get stronger; the 5% contour is barely visible on the right hand side of the top left panel. The average overdensity in this plot is about 8% compared to about 4% in Figure 2. The significance level has also increased, overdensities in almost all the QSO subsamples is above 90%. This increase occurs despite the lower numbers of QSOs in Figure 6 compared to Figure 2.

Aside from magnification bias, support for the lensing hypothesis and against dust obscuration is presented by the behavior of the overdensity as a function of position on the $z_{Q,min}$ vs. $m_{Q,lim}$ (or $f_{Q,min}$) plane. The strongest correlations are seen for QSOs at intermediate redshifts ($z_{Q,min} \sim 1.0$). This is the optimal location of sources for lenses at $z_l \sim 0.1 - 0.3$. On the other hand, Galactic dust should not be able to differentiate between QSOs based on their redshifts. Also, the effects of single wavelength band magnification bias are apparent from Figure 2-5: in any given figure correlations get stronger for brighter QSOs.

We conclude that the cross-correlation signal between 1 Jy QSOs and APM galaxies in our sample is due to weak lensing of QSO by the galaxies and associated dark matter.

Additional independent confirmation of the lensing origin of the QSO-galaxy associations in general comes from a recent study by CS99 who detect anticorrelations between faint optically selected QSOs and foreground groups of galaxies. Because these authors used QSO and galaxy samples that are different from ours we cannot directly compare our respective results. However if all the existing QSO-galaxy association observations are to be explained by a single process then the combination of the results presented here, in WI98 and in CS99 rule out the dust hypothesis. For positive correlation results, as seen in this work, one invokes dust foreground to both QSOs and galaxies, i.e. Galactic dust, to make both QSOs and galaxies overdense in some regions of the sky and underdense in others. For anticorrelation results, as detected in CS99, one needs to invoke dust *intrinsic* to the galaxy groups and clusters to obscure QSOs only in the directions of the lenses. Thus two very different types of dust are needed to explain the two phenomena, while lensing magnification bias accounts for both types of observations: anticorrelations are predicted with QSO samples flux-limited below the turnover in the number counts and positive correlations are predicted for samples limited above the turnover.

5. ANGULAR SCALE OF CORRELATIONS

It is apparent from Figures 2-5 that the amplitude of the cross correlation signal decreases with the angular scale. For example, the representative overdensity in Figure 3 ($\theta = 30'$) is 10%, and drops to $6-7\%$ on Figure 5 ($\theta = 60'$). Note that the statistical significance stays roughly the same on both scales. If the signal originates entirely from small scales, $< 30'$, then one would expect the galaxy overdensity to scale as $\sim 1/\theta^2$. The observations indicate a much slower decline, $\sim 1/\sqrt{\theta}$, implying that the signal is not limited to $< 30'$, but an appreciable contribution arises from $\sim$degree scales.

Ideally, we would like to extend the type of analysis carried out in the previous Sections to scales

smaller, and larger than $30' - 60'$. However, on scales larger than about a degree we run into a problem with APM plate boundaries because the useful area on each plate is limited to 2.5° around the plate center. To look for correlations on scales substantially larger than a degree one would need to match adjacent plates, a task too uncertain when the signal being sought after is of the order of a few percent at best.

On scales smaller than about $30'$ we run into a different problem. The numbers of galaxies drop significantly as the circular area around each QSO is decreased. Because there are not that many QSOs to start with splitting them futher into $m_{Q,lim}$ or $f_{Q,min}$, and $z_{Q,min}$ subsamples is not feasible. To look for signal on smaller scales we combine QSOs into much larger subsamples and plot radial density gradients. Using our full QSO sample, we find no radial galaxy gradients around QSOs on these small scales. Thus we conclude that the galaxies selected as having $18.5 < m_{red} < 20$, with no color cut are tracing the large scale structure on $\sim 10h^{-1}$ Mpc scales, but not the more compact structures on $\sim 1 - 2h^{-1}$Mpc scales.

6. GALAXY SELECTION CRITERIA AND CORRELATIONS

The lack of radial gradient of galaxies within $30'$ around 1 Jy QSOs is in apparent contradiction with the results of BM95 who detect strong correlations on $\theta < 10'$, but see no signal beyond that scale.

We suggest that the discrepancy arises because BM95 and the present work use different galaxy selection criteria and thereby are studing lensing properties of different populations of galaxies, which apparently trace dark matter on different scales.

The two populations are primarily distinguished by their angular size and apparent magnitudes. Our galaxies have $18.5 < m_{red} < 20$ and can have such small angular sizes that they appear unresolved on one set of APM plates (blue) As a result a non-negligible fraction of galaxies in this study, and those in WI98 do appear point-like on the blue plates. (WI98 find that these objects contribute significantly to the detected signal.) BM95 select galaxies with $m_{red} < 19.5$, and insist that they have a large enough angular extent to be resolved on both blue and red plates. Furthermore, the average angular size of BM95 galaxies, as indicated by the semi-major axes of their images on the APM plates is about 1.5 times larger than those of our galaxies. Thus, BM95 use galaxies that are roughly 1.5 times bigger and about 4 times brighter than those in our sample.

Assuming that the two sets of galaxy populations are at the same redshift, $z_l \sim 0.1 - 0.3$, and remembering that the correlations in the present study extend to a $\sim$ degree, while those in BM95 are confined to $< 10'$, we are led to conclude that intrinsically brighter, bigger galaxies trace compact, $\sim 1 - 2h^{-1}$ Mpc mass concentrations, while fainter smaller galaxies trace more extended, smaller contrast mass concentrations on $\sim 10h^{-1}$ Mpc scales. This is, of course, just a speculation; more evidence is needed to support this claim. Other possibilities should also be considered. For example, the two populations of galaxies can be at different redshifts, with BM95 galaxies being twice as close to the observer as those in the present study. If BM95 galaxies are relatively nearby, say at a typical redshift of $\lesssim$0.1, then difference in Σ_{crit}, critical surface mass density for lensing between the location of BM95 galaxies and those in the present work will have to be taken into account.

It is worth noting that regardless of the angular scale of associations the galaxies primarily responsible for the signal are red, with B$-$R greater than about 2 (WI98; BM95; Benítez & Martínez-González 1997). These red galaxies are probably mostly ellipticals, whose distribution is believed to be more biased with respect to mass than that of bluer, presumably mostly spiral galaxies.

7. CONCLUSIONS AND DISCUSSION

In this paper we have extended the work of WI98 to a sample of 1 Jy radio selected QSOs. We have searched for and found correlations of these radio QSOs and red APM galaxies on scales of $30'$ and $60'$. We demonstrate that observed correlations are qualitatively consistant with a gravitational lensing explanation and are inconsistant with a dust obscuration model. The detected overdensity of galaxies around these radio selected QSOs is larger than that found in WI98 for a sample of optically selected QSOs, on similar angular scales. We ascribe the difference to double magnification bias.

For our galaxy sample we find no radial gradients in galaxy density around QSOs on $< 30'$ scales. This is in contradiction with the work of BM95, who also use 1 Jy QSOs and APM galaxies. We suggest that the discrepancy is due to differences in galaxy sample selection. The difference in selection criteria translate, on the average, into BM95 galaxies being about 1.5 times bigger in radius and about 4 times brighter than those in our current sample. We speculate that B95 population of galaxies are better tracers of compact $\sim 1 - 2h^{-1}$ Mpc structures at $z \sim 0.1 - 0.3$, while our galaxies trace more extended structures, $\sim 10h^{-1}$ Mpc in a similar redshift.

In this paper we have argued that the most likely explanation of the correlations is weak gravitational lensing. We have shown that qualitatively the correlations follow lensing expectations. What does not follow the predictions of standard lensing is the amplitude of these correlations.

The amplitude of correlations found in this work is greater than that in WI98, which already exceed the predictions of theoretical models. As dicussed extensively in WI98, the analytical models of Dolag and Bartelmann (1997) and Sanz et al. (1997) and phenomenological predictions using the observed properties of APM galaxies under-predict the amplitude of the overdensity on degree scales by a factor of $5 - 10$. In order to bring the models in line with the observations, assuming that our model of light propagation through the universe is correct, requires a change in the important parameters that describe either the sources or the foreground lenses. WI98 consider two possiblities in some detail. Either, (1) the source population has very steep magnitude-number counts at $z > 1$, or (2) galaxies are biased low with respect to mass, i.e. σ_8, the rms dispersion in mass within $R = 8h^{-1}$Mpc spheres, is much larger than one. WI98 point out that neither of these options is likely in light of other observations and that, likewise, appropriate combinations of these two explanations lead to numbers which are also out of the acceptable range of the parameter space. Currently we have no explanation for the disagreement of the models and observations. Clearly, more work is required both on observational and theoretical fronts to tackle this problem.

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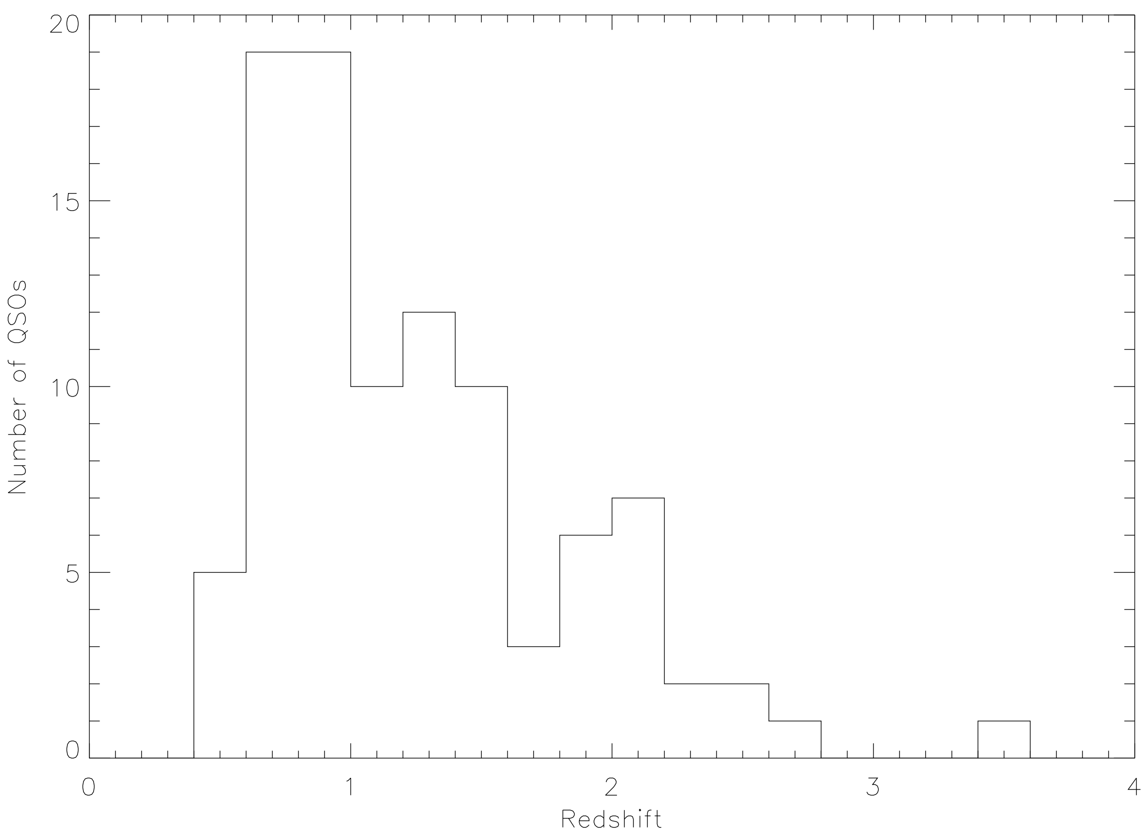

Fig. 1.— Histogram of the number of 1 Jy QSOs versus redshift used in this study.

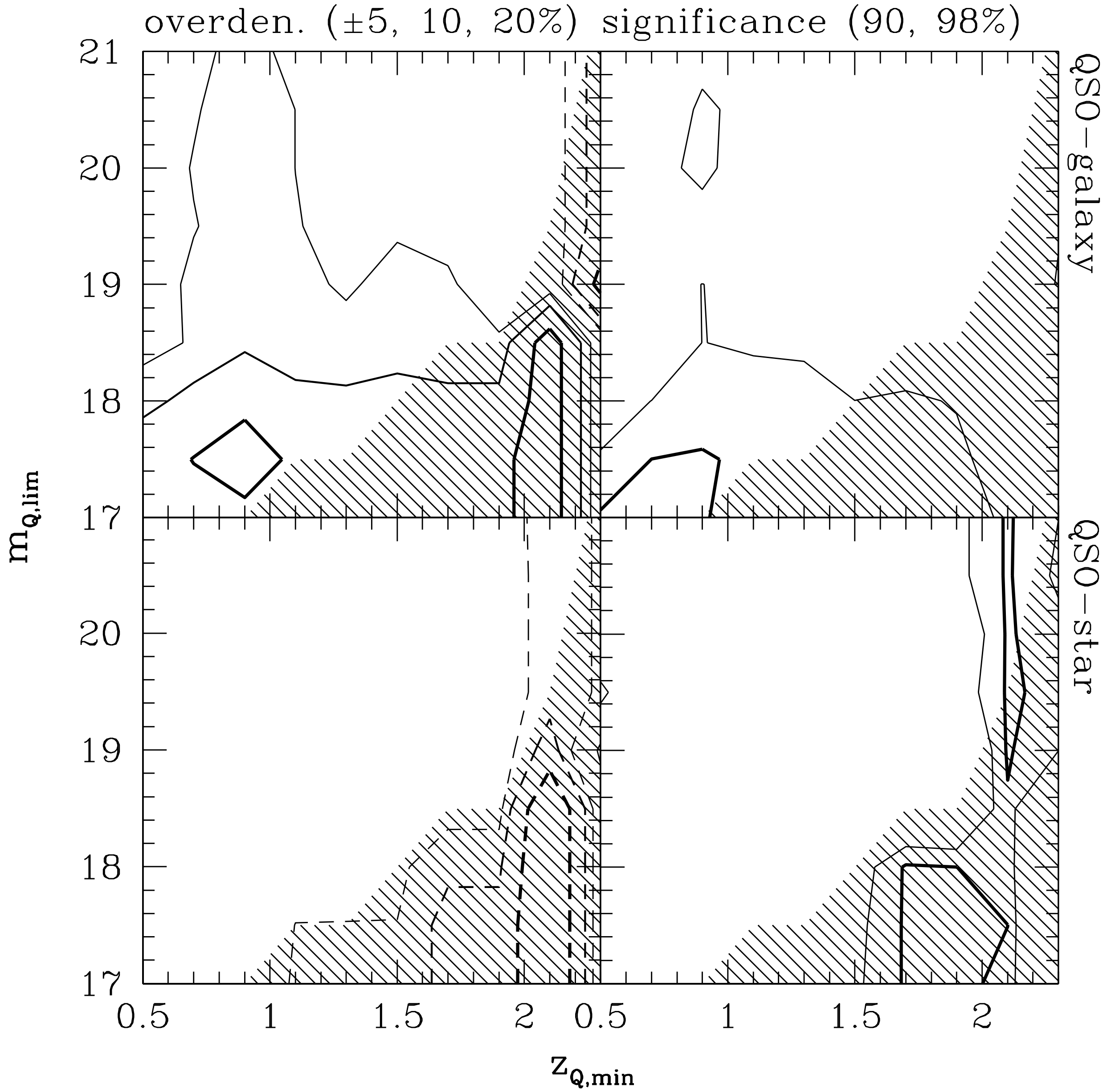

Fig. 2.— Overdensity and statistical significance contour plots for 30′ radial regions around QSOs with $f_{Q,min} = 1.0$Jy as the limiting optical magnitude changes. The top (bottom) panels are the QSO-galaxy (QSO-star) correlations, estimated as the overdensity of galaxies (stars) around QSOs. The left (right) panels show overdensity (statistical significance). Shaded regions have less than 5 QSOs contributing to the estimate. (See text for further details.)

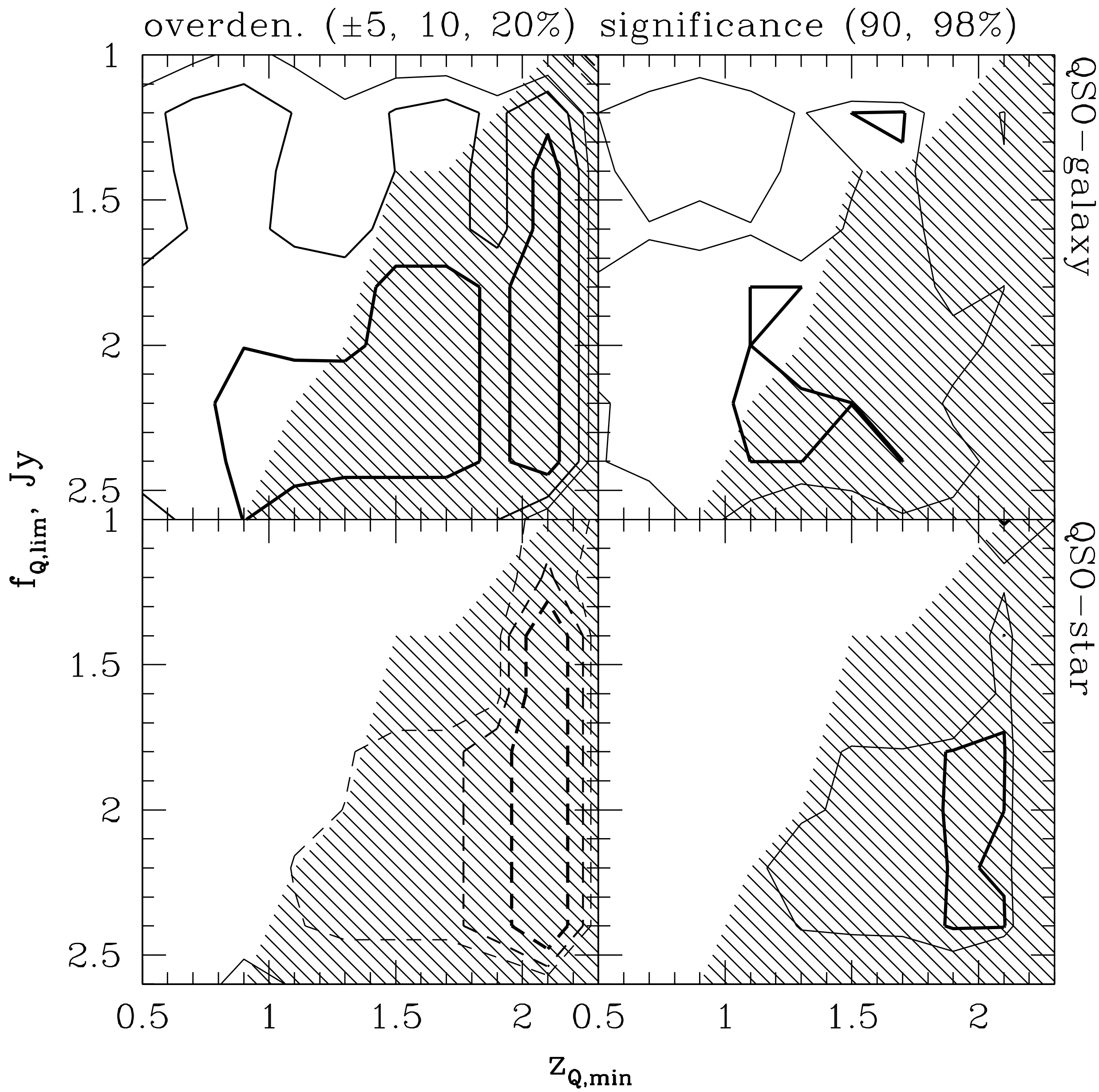

Fig. 3.— Overdensity and statistical significance contour plots similar to Figure 2 except that all optical magnitudes are used and $f_{Q,min}$ changes.

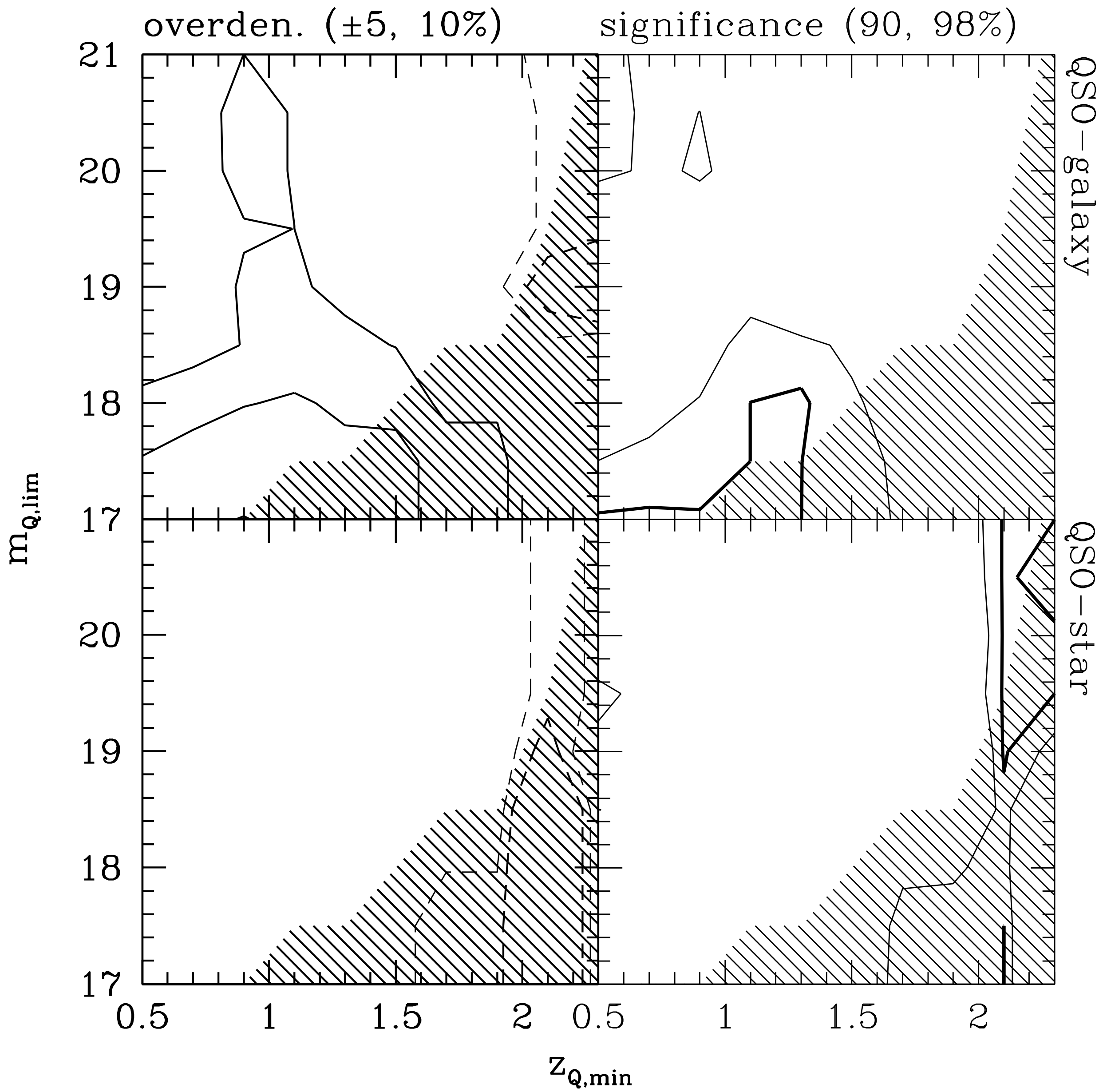

Fig. 4.— Same as Figure 2, but for 60′ radial regions.

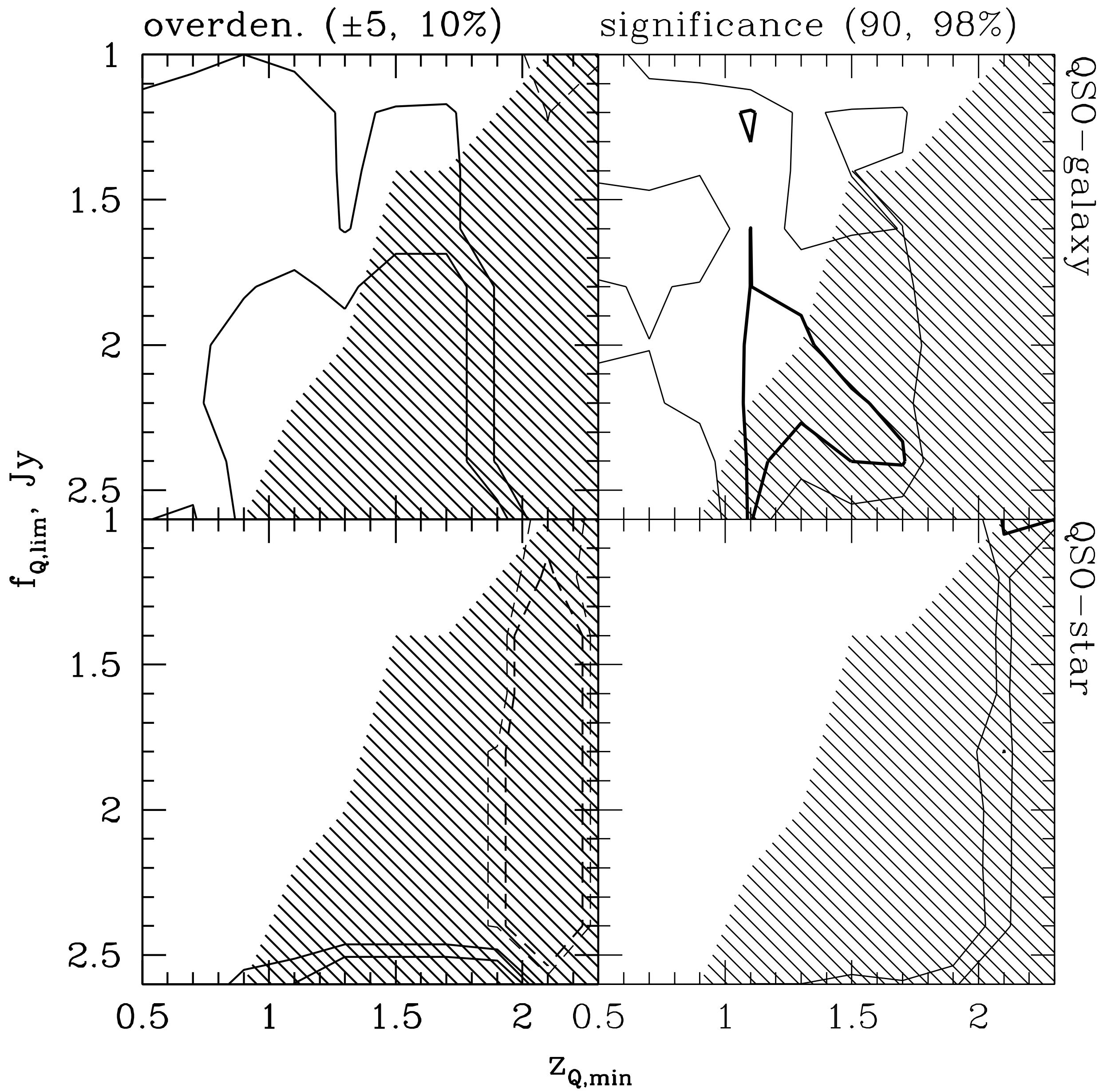

Fig. 5.— Same as Figure 3, but for 60′ radial regions.

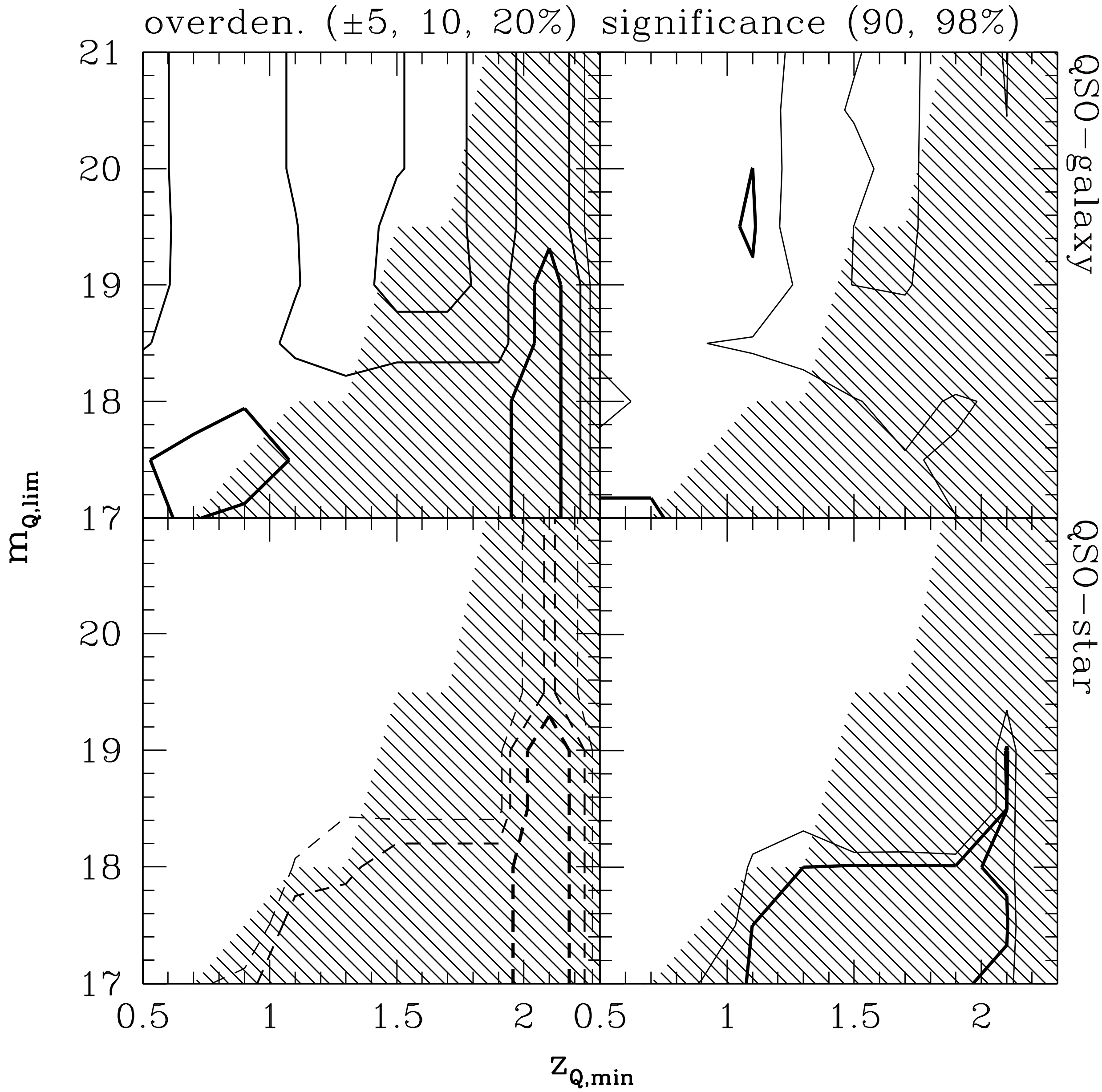

Fig. 6.— Overdensity and statistical significance contour plots similar to Figure 2 except that $f_{Q,min} = 1.25$ Jy as the limiting optical magnitude changes.